NACA RM 56B07

RM 56B07

RESEARCH MEMORANDUM

ELEVATED-TEMPERATURE FATIGUE PROPERTIES OF TWO TITANIUM ALLOYS

By William K. Rey

University of Alabama

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

April 24, 1956

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SUMMARY

An investigation was conducted to evaluate the unnotched fatigue properties of 3Mn Complex and 3Al-5Cr titanium alloys at elevated temperatures. Fatigue studies were conducted for each alloy at room temperature, 200°, 400°, 600°, 800°, and 1,000° F. The results are presented in tabular form and as curves of stress versus cycles to failure for each test temperature. The endurance strength at 10,000,000 cycles for the 3Mn Complex alloy decreased from 79,000 psi at room temperature to 26,500 psi at 1,000° F. The endurance strength at 10,000,000 cycles for the 3Al-5Cr alloy decreased from 91,000 psi at room temperature to 46,500 psi at 1,000° F. The decrease in endurance strength with an increase in temperature is shown by a curve of endurance strength versus temperature for each alloy.

INTRODUCTION

During the past few years metallurgical research has provided the engineer with alloys of titanium that are taking their place as important structural materials. These alloys are of particular interest to the aircraft industry since they possess a unique combination of mechanical properties – lightness, high strength, general resistance to environmental attack, and retention of strength at moderately elevated temperatures. To make the most effective use of these alloys, it will be necessary for the designer to have available the mechanical properties for various types of loading under different environmental conditions.

For many applications, the behavior of a material when it is subjected to repeated stressing is of prime importance. This is true since many of the structural components are subjected to repeated loading and unloading. This investigation was undertaken to determine the unnotched fatigue properties of two titanium alloys at temperatures up to 1,000° F because of the potential use of titanium alloys in this temperature range.

This investigation was initiated under the sponsorship of the University Research Committee of the University of Alabama and completed with the University Research Committee and the National Advisory Committee for Aeronautics as cosponsors. The University Research Committee supplied funds for the necessary equipment and the National Advisory Committee for Aeronautics furnished the operating funds. The material required for preparation of the test specimens was donated by the Mallory-Sharon Titanium Corporation of Niles, Ohio.

MATERIAL

The alloy designated 3Mn Complex titanium alloy was supplied as hot-rolled and cleaned 1/2-inch-diameter round rod with all material coming from the same heat. The chemical composition by weight of this heat as determined by the Mallory-Sharon laboratory was as follows:

Carbon, percent	0.03
Nitrogen, percent	0.010
Hydrogen, percent	0.012
Iron, percent	0.93
Manganese, percent	3.34
Chrominum, percent	1.07
Vanadium, percent	1.03
Molybdenum, percent	1.01
Titanium	Bal.

The room-temperature mechanical properties were determined using American Society for Metals standard 5/16-inch tension specimens. These tests were performed in a Baldwin 60,000-pound universal testing machine with a Huggenberger Tensometer used to measure strains. The average room-temperature mechanical properties from three tests were as follows:

Ultimate strength, psi	147,900
Proportional limit, psi	126,000
Yield strength (0.2-percent offset), psi	134,750
Young's modulus, psi	16,200,000
Elongation in 1 inch, percent	24
Reduction of area, percent	57.8
Rockwell hardness	33.8C

The average tensile stress-strain curve for the 3Mn Complex alloy is shown in figure 1.

The second alloy, which is designated 3Al-5Cr titanium alloy, was also supplied as hot-rolled and cleaned 1/2-inch-diameter round rod with all material coming from the same heat. The chemical composition by weight as determined by the Mallory-Sharon laboratory was as follows:

Carbon, percent	0.05
Nitrogen, percent	0.036
Hydrogen, percent	0.011
Iron, percent	0.25
Aluminum, percent	3.47
Chromium, percent	4.94
Titanium	Bal.

The room-temperature mechanical properties were determined by the same procedure used for the other alloy. The average room-temperature mechanical properties for the 3Al-5Cr alloy were as follows:

Ulitmate strength, psi	140,800
Proportional limit, psi	111,800
Yield strength (0.2-percent offset), psi	125,300
Young's modulus, psi	15,500,000
Elongation in 1 inch, percent	21
Reduction of area, percent	57.8
Rockwell hardness	35.5C

The average tensile stress-strain curve for the 3Al-5Cr alloy is shown in figure 2.

APPARATUS AND PROCEDURE

Figure 3 shows the Krouse high-speed, high-temperature, repeated-stress machine used for all fatigue tests. This machine loads the specimen as a simple beam with a constant bending moment throughout the length of the specimen. It is equipped with a Marshall furnace and Foxboro potentiometer controller that permit testing at room temperature and in the range from 200° to 1,800° F with an accuracy of ±2° F.

Prior to testing, it was necessary to perform a load calibration to determine the load necessary to balance the weight of the driving motors and specimen holders. This was accomplished by using a dummy specimen to which two type A-8 SR-4 electric strain gages were attached. Loads were applied in 1-pound increments and the strains determined for each load. Curves of load versus strain were plotted to determine the tare load. This load calibration was confirmed by testing a number of stainless-steel specimens in this machine and comparing the results with data obtained from another machine. This check showed excellent agreement in the results obtained from the two machines.

The furnace temperature is controlled during testing by means of a Chromel-Alumel thermocouple placed at the center of the furnace midway between the specimen and the furnace wall. To determine the correlation between the temperature of this control thermocouple and the specimen temperature, an iron-constantan thermocouple was attached to the center of a specimen. For each of the test temperatures, a series of readings was taken to determine the difference in temperature at the two thermocouple locations. These data showed that after temperature equilibrium was reached there was a maximum of 2° F difference in temperature at the two locations. An additional investigation showed that the temperature was constant throughout the length of the specimen.

The dimensions of the specimens used for all fatigue tests are given in figure 4. These specimens were prepared from 1/2-inch-diameter rod and then polished. The machining marks were removed with 3/0 emery cloth, and 400-A Durite paper was used for the final polish. All circumferential scratches were removed by polishing parallel to the longitudinal axis of the specimen while it slowly rotated in a lathe. Approximately 0.002 inch of the material was removed during the polishing operation.

The specimens were inserted in the furnace at room temperature and rotated at zero stress while the furnace temperature was increased to the test temperature. The testing temperature was attained in 45 minutes. An additional 15 minutes was allowed to obtain temperature equilibrium before applying the load. All tests were conducted at a speed of 4,800 cycles per minute. The test temperatures were room temperature, 200°, 400°, 600°, 800°, and 1,000° F.

RESULTS AND DISCUSSION

The results of the fatigue tests of the 3Mn Complex alloy are presented in tabular form in table I and as curves of nominal stress versus cycles to failure in figures 5(a) to 5(f). The endurance strengths at 10,000,000 cycles from these curves, are compared in the following table:

Temperature, °F	Endurance strength, psi	Endurance ratio
Room temperature	79,000	0.53
200	65,500	.44
400	64,000	.43
600	55,500	.38
800	45,000	.30
1,000	26,500	.18

The endurance ratios in this table were computed as the ratio of the endurance strength at 10,000,000 cycles to the ultimate strength at room temperature. Although this ratio is not the true endurance ratio for the elevated temperatures, it is a measure of the reduction in strength as temperature increases. As shown in the table, the endurance strength decreased from 79,000 psi at room temperature to 26,500 psi at 1,000° F. The reduction in strength is shown graphically by a curve of endurance strength versus temperature in figure 6.

The curves of stress versus cycles to failure for the 3Mn Complex alloy exhibit small scatter at room temperature, 200°, and 800° F. While the data at 400° and 600° F show greater scatter, it is not unreasonable. The small number of specimens available for testing at 1,000° F was due to the limited amount of available material. However, a sufficient number of tests were performed at 1,000° F to give a reasonable indication of the endurance strength at this temperature.

The results of the fatigue tests of the 3Al-5Cr alloy are presented in tabular form in table II and as curves of nominal stress versus cycles to failure in figures 7(a) to 7(f). The endurance strengths at 10,000,000 cycles from these curves are compared in the following table:

Temperature, °F	Endurance strength, psi	Endurance ratio
Room temperature	91,000	0.65
200	84,000	.60
400	79,500	.56
600	73,400	.52
800	62,250	.44
1,000	46,500	.33

The endurance ratio was computed as for the 3Mn Complex alloy. The endurance strength decreased from 91,000 psi at room temperature to 46,500 psi at 1,000° F. The curve of endurance strength versus temperature is shown in figure 6.

Some of the scatter in the fatigue results may be attributed to the fact that neither material was annealed after rolling. Since the temperature calibration was performed under static conditions, it is possible that the rotation of the specimen produced a small temperature change that would further account for the scatter in the test results.

In table III the ratios of endurance strength to weight of the two titanium alloys and four aluminum alloys are compared at four temperatures. The endurance strengths of the titanium alloys at 300° and 500° F were obtained from figure 6 by interpolation. The endurance strengths of the aluminum alloys were obtained from reference 1. This comparison shows that the titanium alloys are superior to the aluminum alloys at all four temperatures on the basis of their ratios of endurance strength to weight. The 3Al-5Cr alloy has a higher ratio of endurance strength to weight at all temperatures than the 3Mn Complex alloy even though it has a lower ultimate tensile strength at room temperature.

It is of interest to note that the curves of endurance strength versus temperature have the same shape for both materials. The small reduction in endurance strength for the 3Mn Complex alloy between 200° and 600° F is surprising when compared with the reduction in endurance strength between room temperature and 200° F. In plotting these curves, the room temperature was taken as 75° F.

CONCLUDING REMARKS

Within the limitations of test scatter, the results of a study of the fatigue properties of two titanium alloys show that both of the alloys have potential use in the temperature range investigated. The 3Al-5Cr alloy has a higher endurance strength than the 3Mn Complex alloy at all temperatures considered in this study even though it has a lower ultimate tensile strength at room temperature.

A comparison of the two titanium alloys with aluminum alloys shows that the titanium alloys are superior on the basis of their ratios of endurance strength to weight.

Further study is needed to complete the evaluation of these alloys. A study of the possible correlation between the endurance strength at elevated temperatures and the stress to rupture at these temperatures would be of value. An investigation of the notch sensitivity at elevated temperatures is also necessary to complete the evaluation for applications involving repeated stressing.

University of Alabama,
University, Ala., May 12, 1955.

REFERENCE

1. Anon.: Strength of Metal Aircraft Elements. ANC-5, Munitions Board Aircraft Committee, Mar. 1955.

TABLE I.- RESULTS OF FATIGUE TESTS OF 3Mn COMPLEX TITANIUM ALLOY

Specimen	Stress, psi	Cycles to failure	Remarks
At room temperature			
10F 2	100,720	7,300	
10F 16	100,280	10,700	
10F 15	98,320	16,800	
10F 12	98,030	18,500	
10F 3	94,270	20,600	
10F 4	90,370	28,700	
10F 11	87,910	64,800	
10F 5	86,320	97,700	
10F 6	84,760	61,100	
10F 7	82,030	144,900	
10F 8	79,980	450,200	
10F 14	79,640	21,713,800	Did not fail
10F 10	79,230	340,400	
10F 9	78,460	14,347,500	Did not fail
At 200° F			
10F 17	83,830	40,100	
10F 18	81,070	24,800	
10F 19	80,580	47,000	
10F 20	76,590	44,400	
10F 21	72,320	88,000	
10F 25	70,650	318,500	
10F 22	69,210	704,800	
10F 24	67,430	2,272,100	
10F 27	66,520	3,618,100	
10F 26	65,930	1,710,000	
10F 31	65,900	13,205,100	Did not fail
10F 29	65,080	1,711,900	
10F 28	64,500	1,456,500	
10F 30	64,350	10,120,800	Did not fail
10F 23	64,230	12,065,200	Did not fail
At 400° F			
10F 38	71,930	32,200	
10F 41	70,060	165,100	
10F 43	69,980	46,500	
10F 39	69,160	1,262,100	
10F 35	68,700	402,400	
10F 42	68,010	38,400	
10F 44	67,590	34,300	
10F 36	66,760	173,300	
10F 40	66,400	80,400	
10F 37	65,380	47,800	
10F 48	65,020	2,003,500	
10F 34	64,670	22,804,000	Did not fail
10F 49	64,140	10,651,900	
10F 46	64,070	1,028,200	
10F 47	63,020	10,286,600	Did not fail
10F 45	61,990	10,041,700	Did not fail

TABLE I.- RESULTS OF FATIGUE TESTS OF 3Mn COMPLEX TITANIUM ALLOY — Concluded

Specimen	Stress, psi	Cycles to failure	Remarks
At 600° F			
10F 51	84,060	4,100	
10F 74	64,000	23,200	
10F 58	63,750	20,300	
10F 57	62,900	135,400	
10F 59	62,870	116,200	
10F 73	62,820	50,200	
10F 60	62,200	30,600	
10F 61	61,530	583,900	
10F 62	61,000	129,300	
10F 75	60,930	156,100	
10F 63	60,490	768,200	
10F 76	60,080	200,000	
10F 64	59,950	1,106,300	
10F 65	59,490	305,400	
10F 66	59,060	130,700	
10F 67	59,060	353,900	
10F 68	57,900	1,542,300	
10F 69	57,250	2,598,400	
10F 70	56,380	3,441,100	
10F 72	54,950	12,090,500	Did not fail
10F 52	43,060	12,406,400	Did not fail
At 800° F			
10F 81	59,030	12,200	
10F 82	57,870	16,200	
10F 83	57,000	14,800	
10F 84	55,960	28,100	
10F 85	55,020	28,200	
10F 86	53,880	34,400	
10F 87	53,190	57,500	
10F 89	52,040	61,900	
10F 90	51,020	102,500	
10F 91	50,000	186,900	
10F 93	49,490	138,300	
10F 94	49,080	209,700	
10F 92	48,160	1,905,300	
10F 97	47,990	664,300	
10F 95	47,540	652,300	
10F 98	47,060	335,700	
10F 99	46,010	888,700	
10F 101	45,460	1,765,300	
10F 100	45,040	10,156,700	
At 1,000° F			
10F 77	54,790	7,800	
10F 78	34,960	214,600	
10F 80	33,500	286,100	
10F 79	32,010	3,131,000	
10F 102	31,000	434,900	
10F 104	29,000	1,092,300	
10F 103	26,370	12,318,800	Did not fail

TABLE II.- RESULTS OF FATIGUE TESTS OF 3A-5C TITANIUM ALLOY

Specimen	Stress, psi	Cycles to failure	Remarks
At room temperature			
9F 6	99,830	26,800	
9F 7	98,240	19,600	
9F 12	97,000	23,200	
9F 4	95,280	36,400	
9F 13	95,020	29,000	
9F 40	94,460	57,100	
9F 41	94,300	105,700	
9F 38	94,090	1,017,000	
9F 39	94,090	12,786,500	Did not fail
9F 14	92,870	57,400	
9F 2	92,490	10,083,200	Did not fail
9F 18	91,720	66,300	
9F 19	91,480	65,400	
9F 17	91,450	54,600	
9F 20	91,060	54,757,300	Did not fail
9F 16	90,710	13,466,000	Did not fail
9F 15	87,120	13,000,000	Did not fail
9F 1	81,220	21,322,500	Did not fail
At 200° F			
9F 21	92,860	58,300	
9F 22	90,150	72,100	
9F 25	89,290	84,300	
9F 23	87,650	45,900	
9F 26	87,220	112,700	
9F 35	86,000	57,000	
9F 33	85,860	75,600	
9F 30	85,770	65,700	
9F 29	85,770	77,100	
9F 36	85,490	184,200	
9F 37	85,290	59,500	
9F 34	85,000	14,160,500	Did not fail
9F 28	84,860	71,500	
9F 32	84,760	101,549,500	Did not fail
9F 31	84,490	51,800	
9F 27	84,010	104,550,400	Did not fail
At 400° F			
9F 56	89,800	28,200	
9F 57	87,860	36,800	
9F 53	84,810	93,500	
9F 54	84,650	45,200	
9F 58	83,870	27,200	
9F 42	82,080	72,400	
9F 60	81,110	65,200	
9F 59	80,870	25,200	
9F 50	80,250	99,972,400	Did not fail
9F 49	79,900	2,284,400	
9F 52	79,230	2,092,900	
9F 48	75,550	22,288,900	Did not fail
9F 47	75,030	12,757,500	Did not fail
9F 46	74,330	14,190,700	Did not fail
9F 45	73,240	19,498,300	Did not fail

TABLE II.- RESULTS OF FATIGUE TESTS OF 3A-5C TITANIUM ALLOY - Concluded

Specimen	Stress, psi	Cycles to failure	Remarks
At 600° F			
9F 74	76,110	8,188,100	
9F 75	76,070	149,300	
9F 62	75,960	37,800	
9F 73	75,200	76,400	
9F 63	74,930	40,000	
9F 71	74,600	98,300	
9F 72	74,240	4,587,000	
9F 61	74,140	4,325,300	
9F 64	74,090	34,900	
9F 70	73,870	14,190,700	Did not fail
9F 69	73,690	13,093,100	Did not fail
9F 68	73,520	4,663,400	
9F 66	72,980	10,216,800	Did not fail
9F 65	71,750	13,975,000	Did not fail
At 800° F			
9F 80	74,000	40,300	
9F 77	72,990	22,900	
9F 82	71,990	27,700	
9F 90	71,000	25,600	
9F 76	70,040	76,600	
9F 89	69,990	19,100	
9F 81	68,990	22,800	
9F 85	67,960	57,100	
9F 84	67,000	26,600	
9F 94	66,510	126,000	
9F 83	65,990	82,600	
9F 91	64,990	148,400	
9F 78	64,990	187,200	
9F 86	64,010	78,500	
9F 92	63,500	90,400	
9F 88	63,010	271,200	
9F 93	62,510	11,859,200	Did not fail
9F 87	61,990	4,996,500	
At 1,000° F			
9F 96	56,990	42,000	
9F 95	54,990	250,500	
9F 97	53,000	417,000	
9F 98	50,510	481,900	
9F 100	50,000	2,406,100	
9F 101	49,000	166,200	
9F 102	47,490	425,000	
9F 103	46,570	12,222,900	Did not fail
9F 99	45,000	11,088,900	Did not fail

TABLE III.- COMPARISON OF RATIOS OF ENDURANCE STRENGTH[a] TO WEIGHT

Material	Weight, W, lb/cu in.	At room temp.		At 300° F		At 400° F		At 500° F	
		F_e	F_e/W	F_e	F_e/W	F_e	F_e/W	F_e	F_e/W
3Mn Ti alloy	0.170	79,000	464,700	65,000	382,400	64,000	376,500	61,500	361,800
3Al-5Cr Ti alloy	.166	91,000	548,000	80,500	484,900	79,500	478,900	77,000	463,900
2014-T6 aluminum alloy	.101	24,000	237,600	15,000	148,500	10,000	99,000	7,000	69,300
2024-T4 aluminum alloy	.100	24,000	240,000	17,000	170,000	13,000	130,000	8,500	85,000
6061-T6 aluminum alloy	.098	17,000	173,500	14,000	142,900	11,000	112,200	5,500	56,100
7075-T6 aluminum alloy	.101	24,000	237,600	13,000	128,700	9,500	94,100	8,000	79,200

[a]In this table, the endurance strength F_e is taken at 10,000,000 cycles.

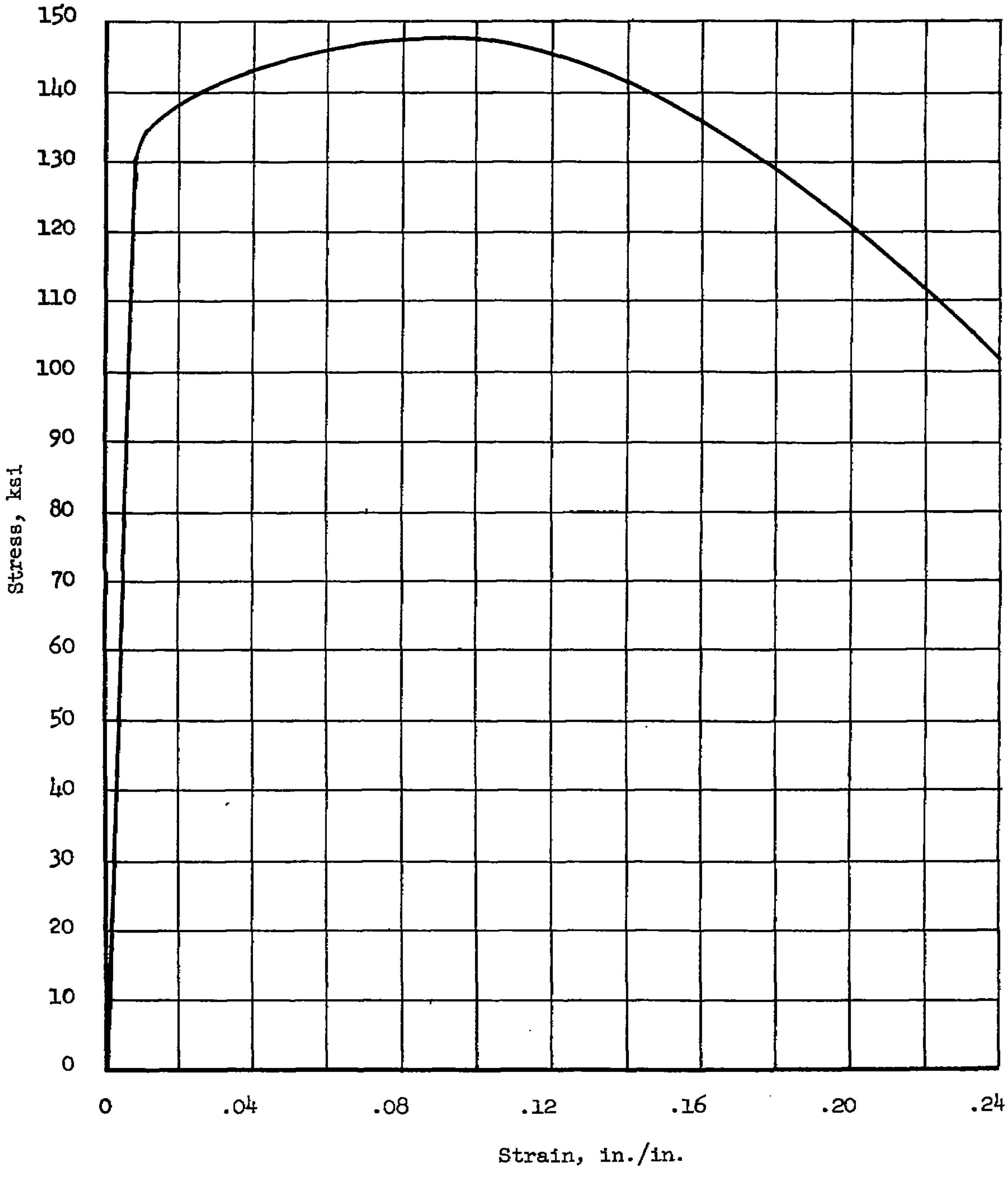

Figure 1.- Tensile stress-strain curve for 3Mn Complex titanium alloy at room temperature.

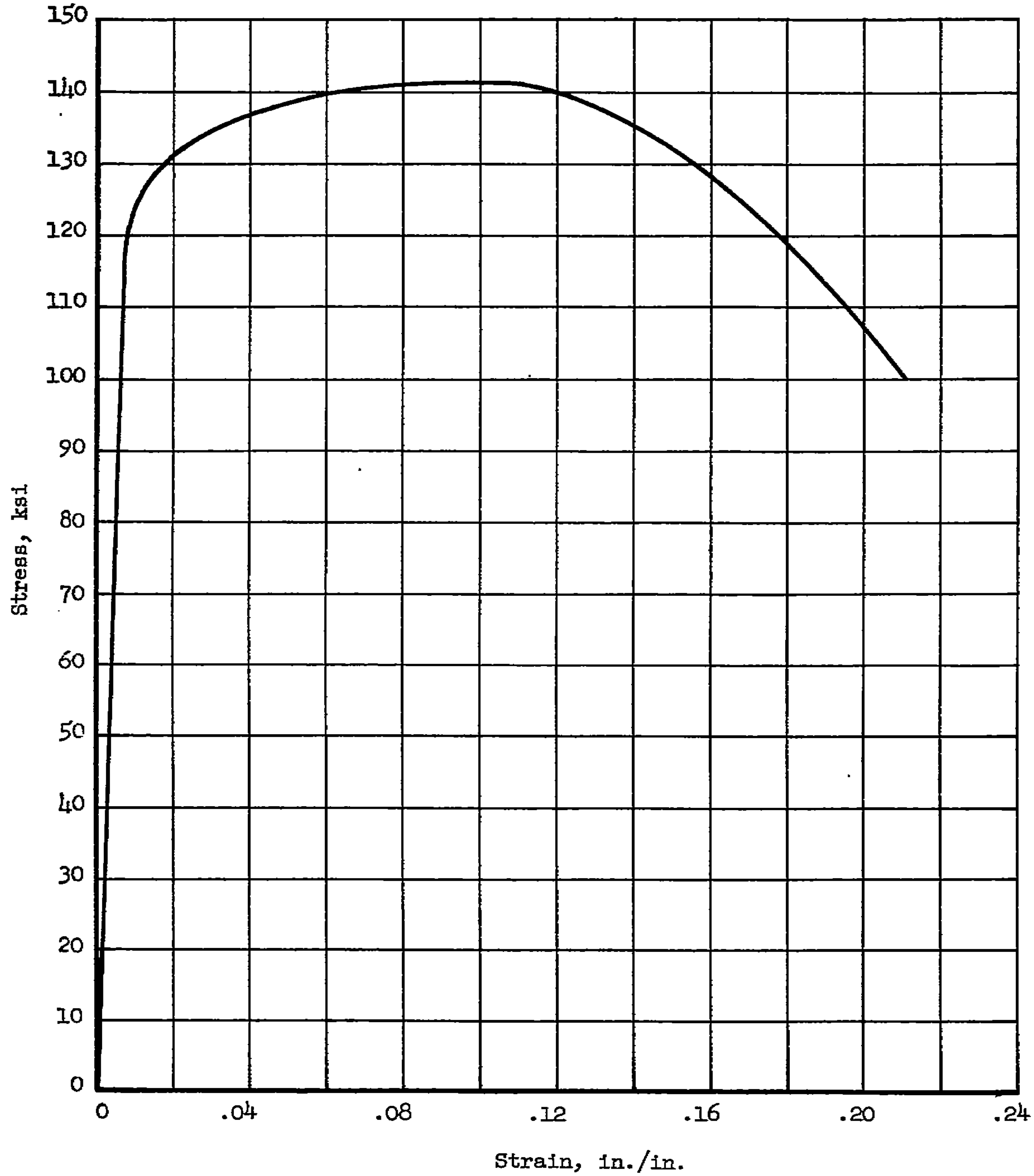

Figure 2.- Tensile stress-strain curve for 3Al-5Cr titanium alloy at room temperature.

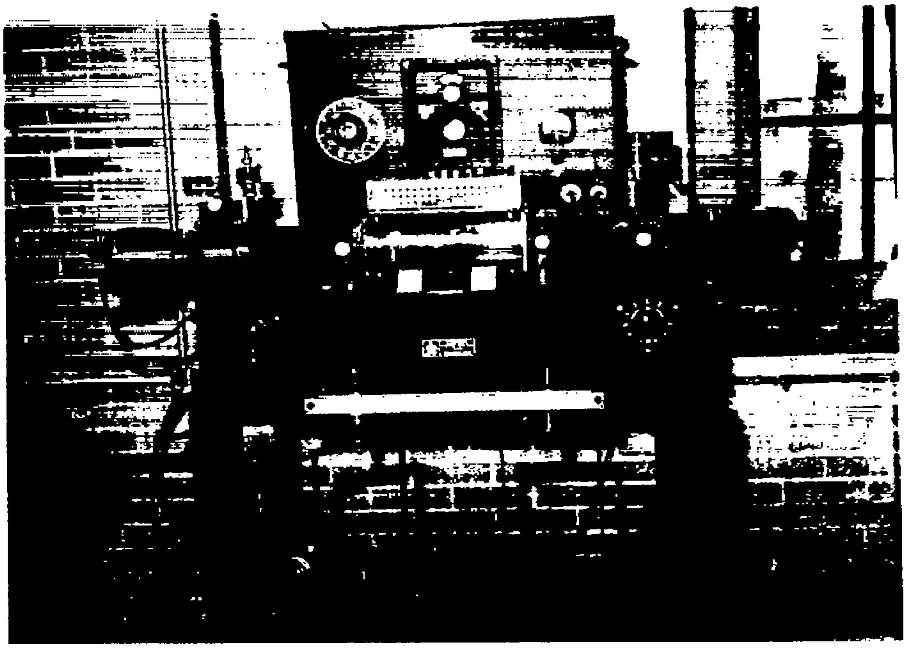

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Figure 3.- Krouse high-speed, high-temperature, rotating-beam fatigue machine.

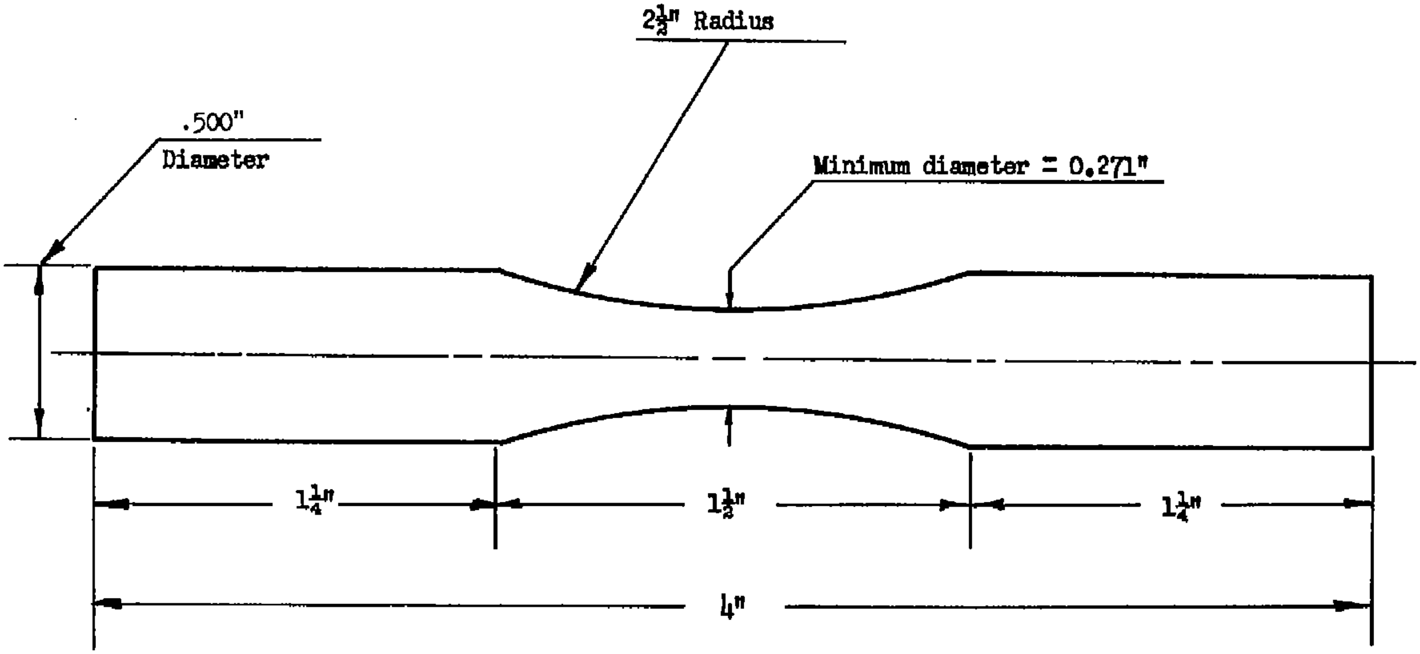
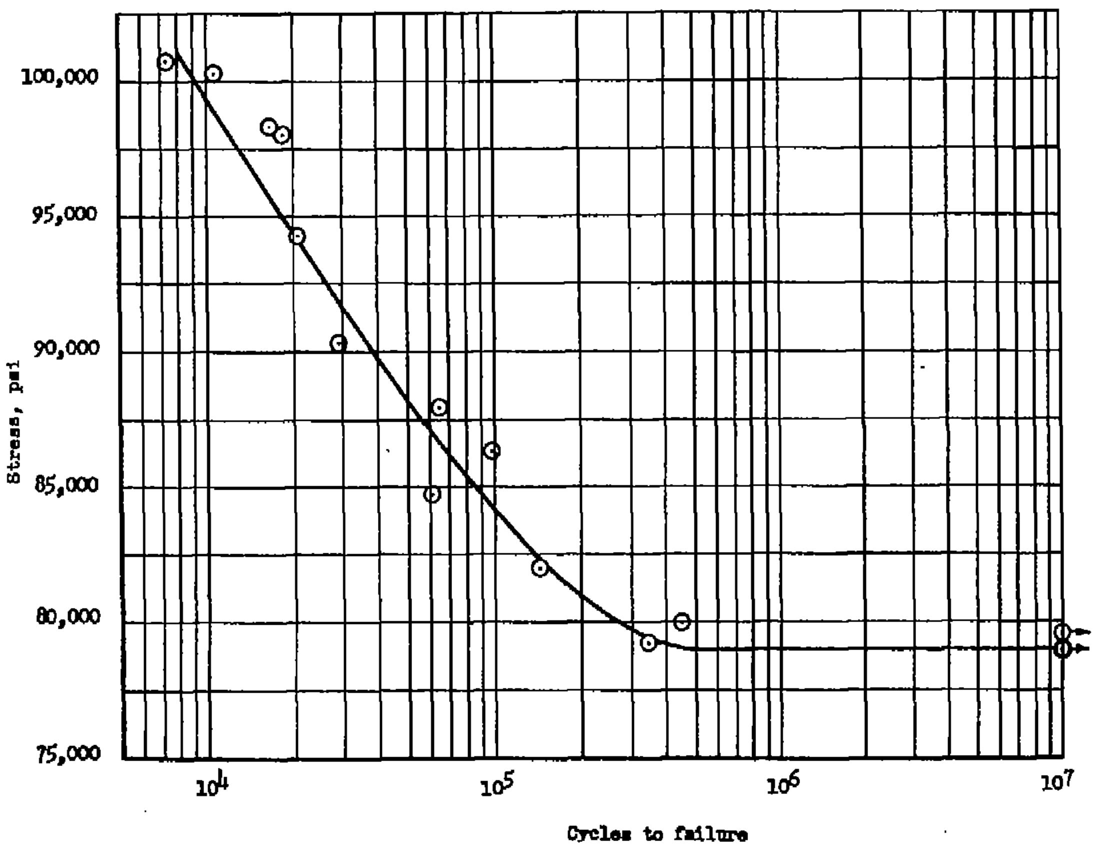
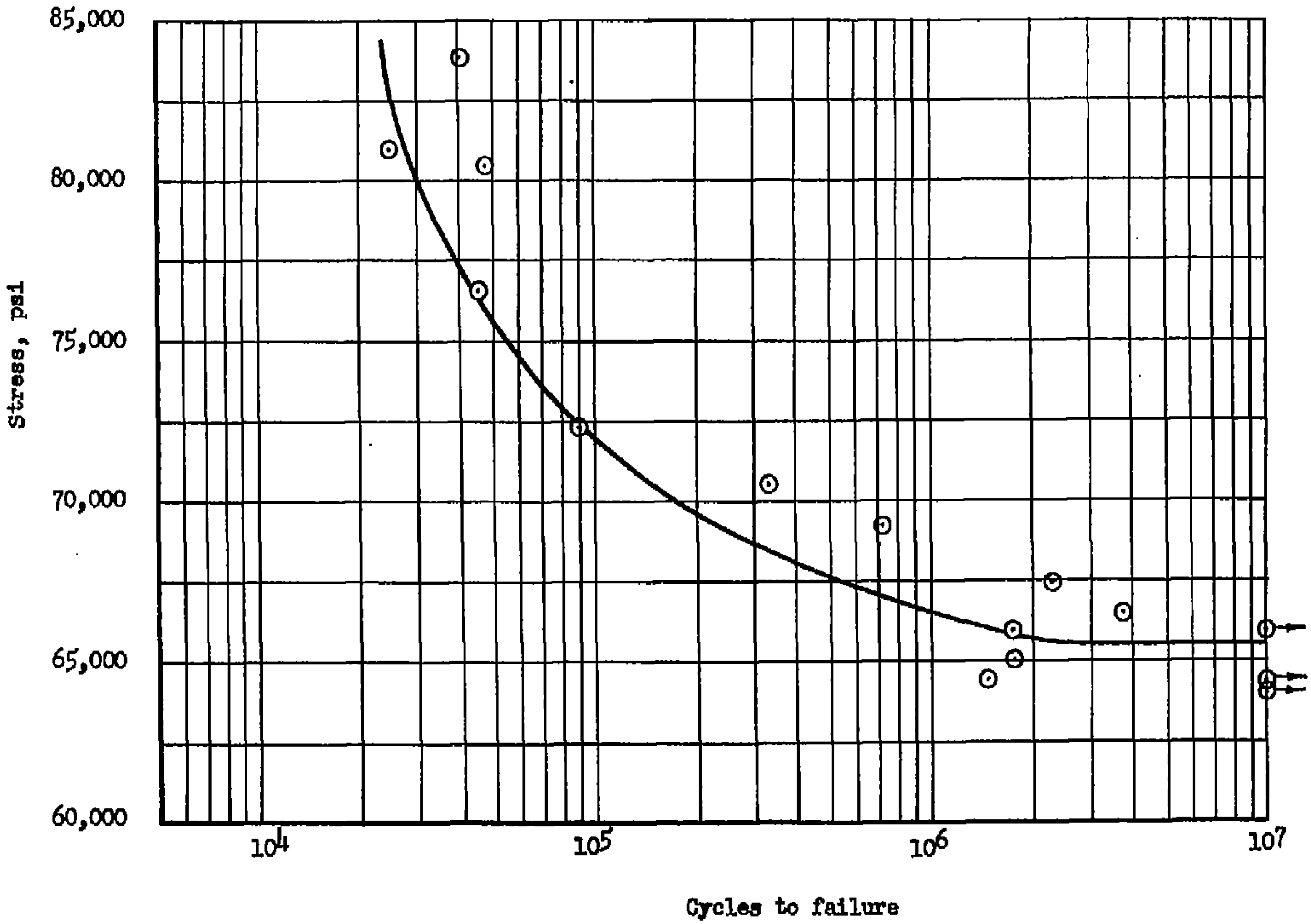


Figure 4.- Dimensions of 1/2-inch-diameter rotating-beam fatigue specimen.



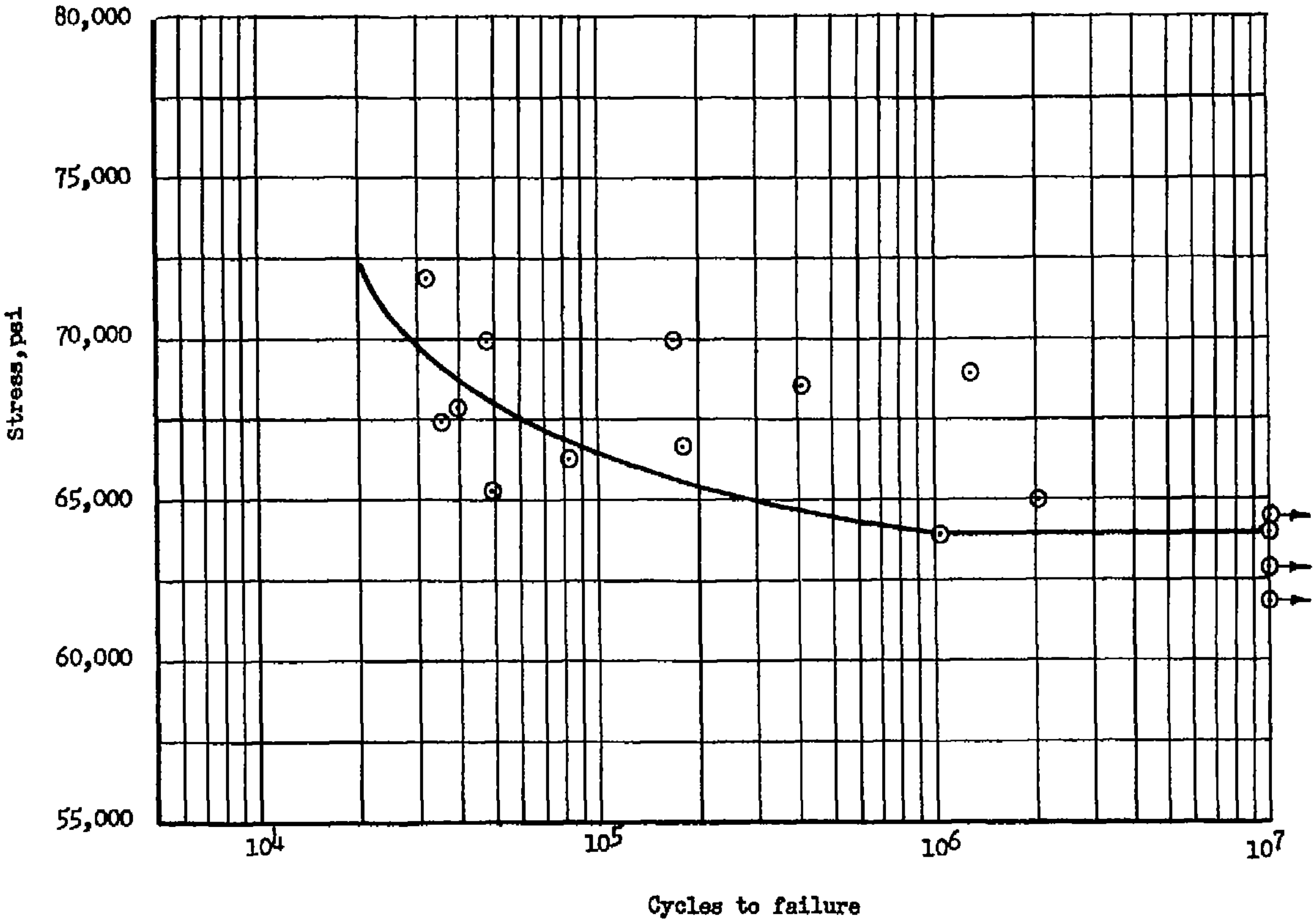
(a) At room temperature.

Figure 5.- Fatigue-test results for 3Mn Complex titanium alloy.



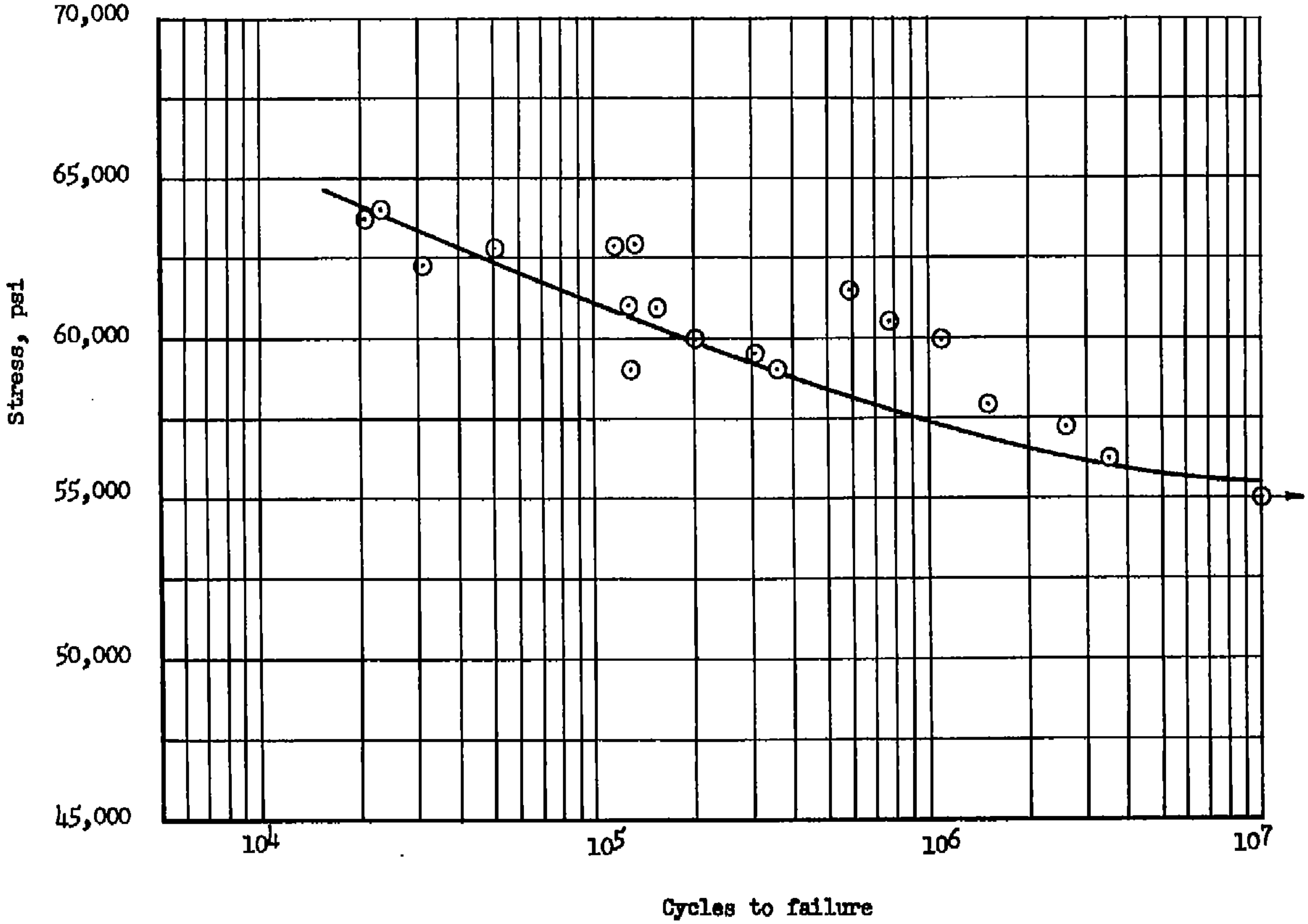
(b) At 200° F.

Figure 5.- Continued.



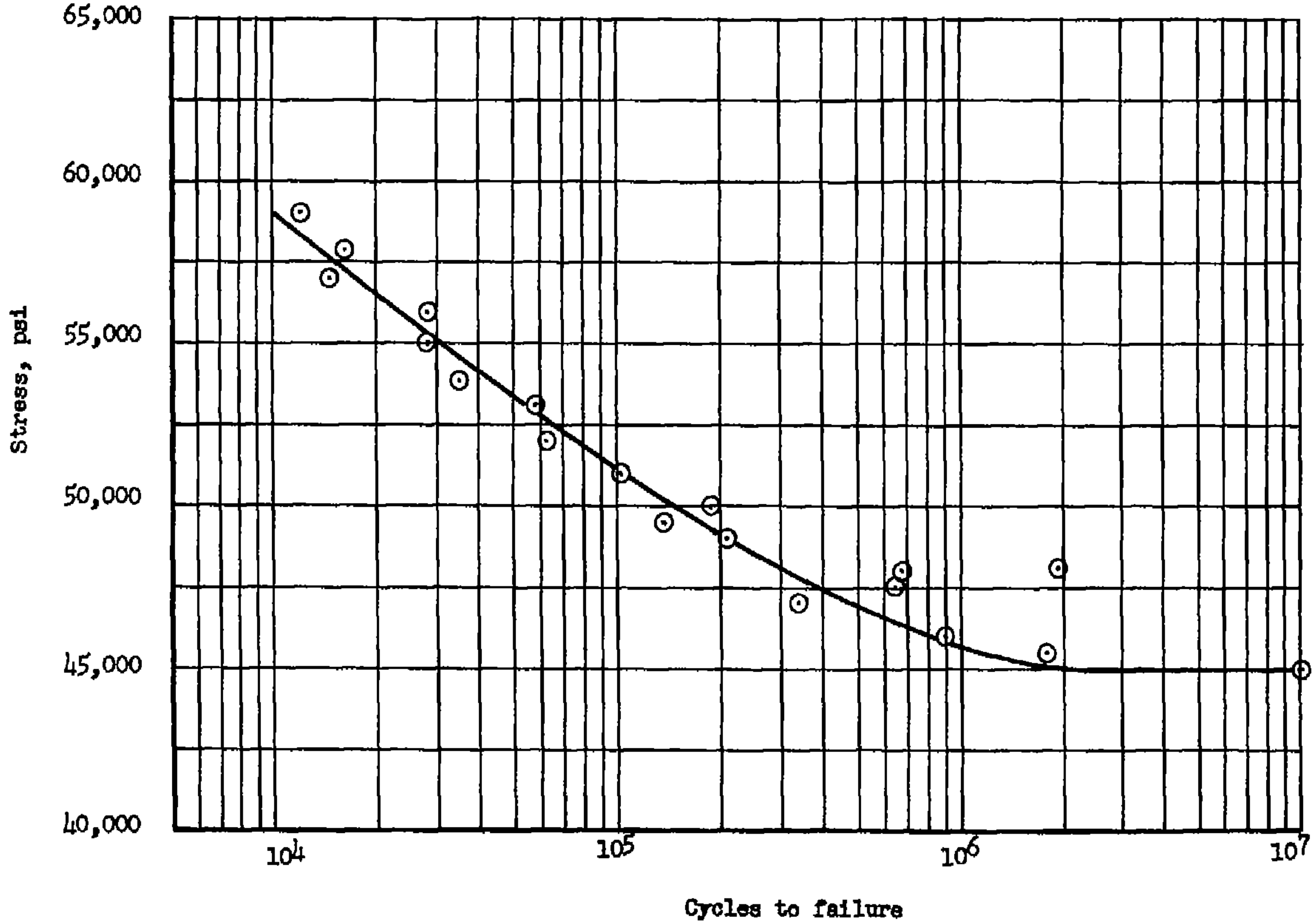
(c) At 400° F.

Figure 5.- Continued.



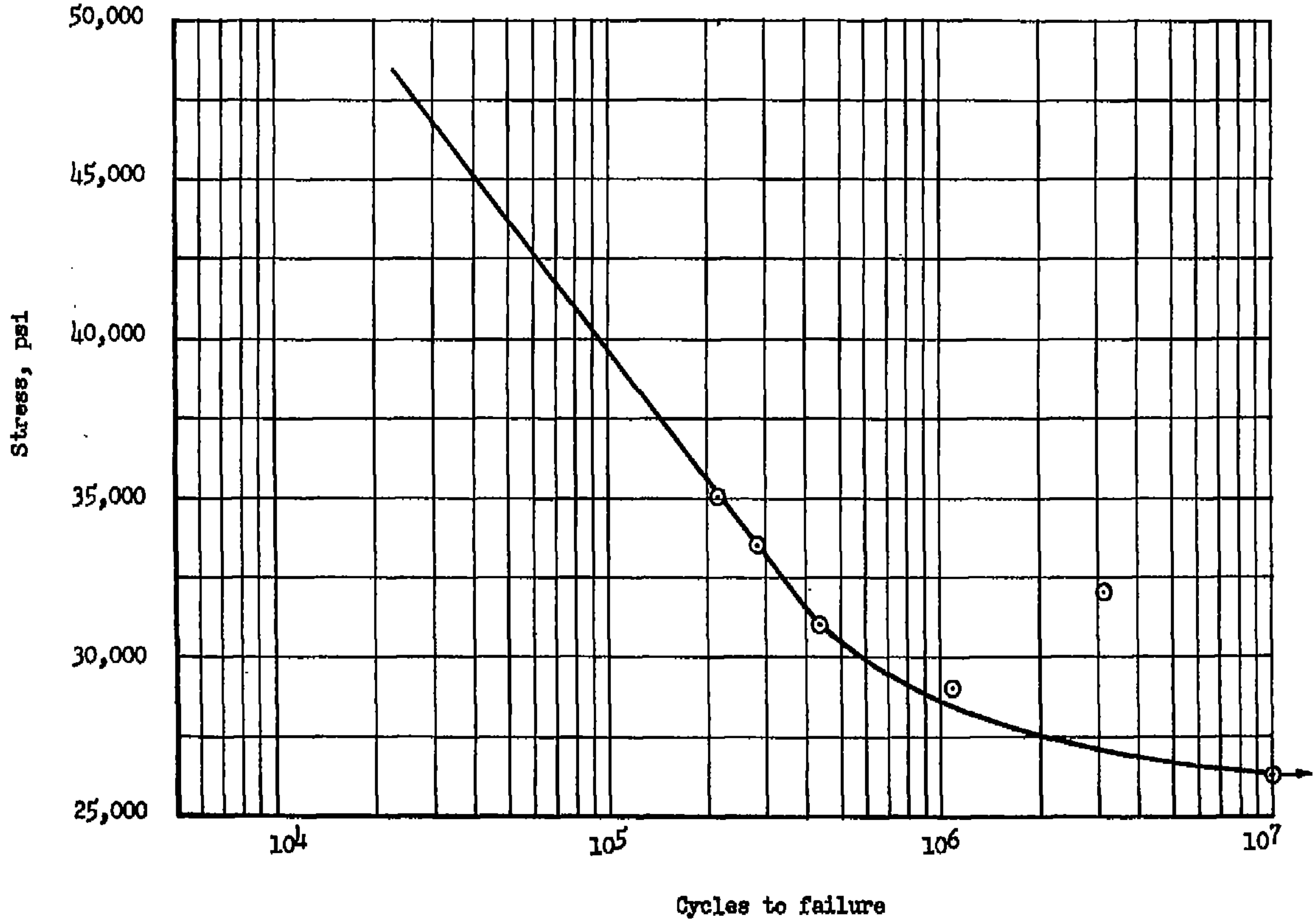
(d) At 600° F.

Figure 5.- Continued.



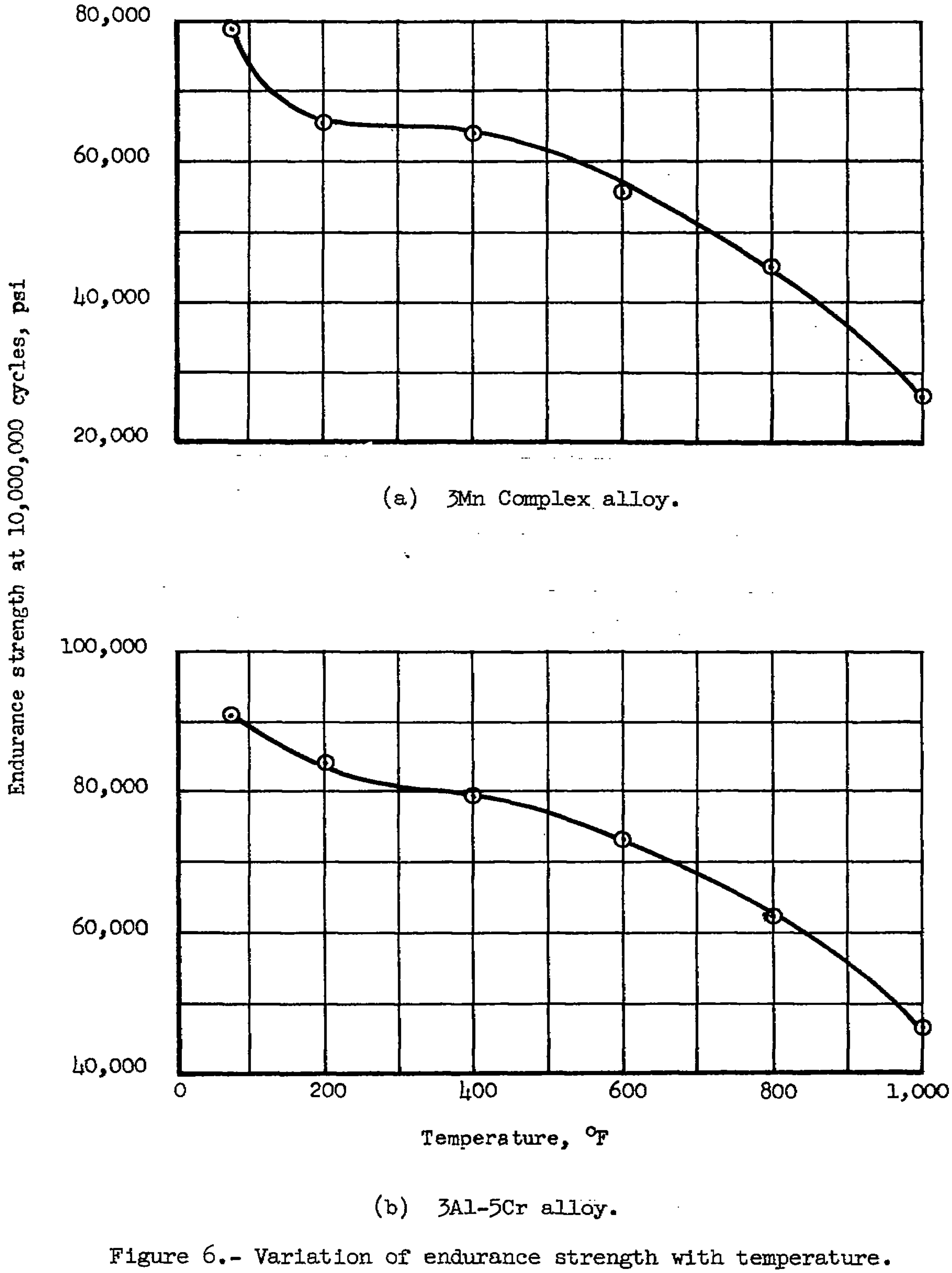
(e) At 800° F.

Figure 5.- Continued.



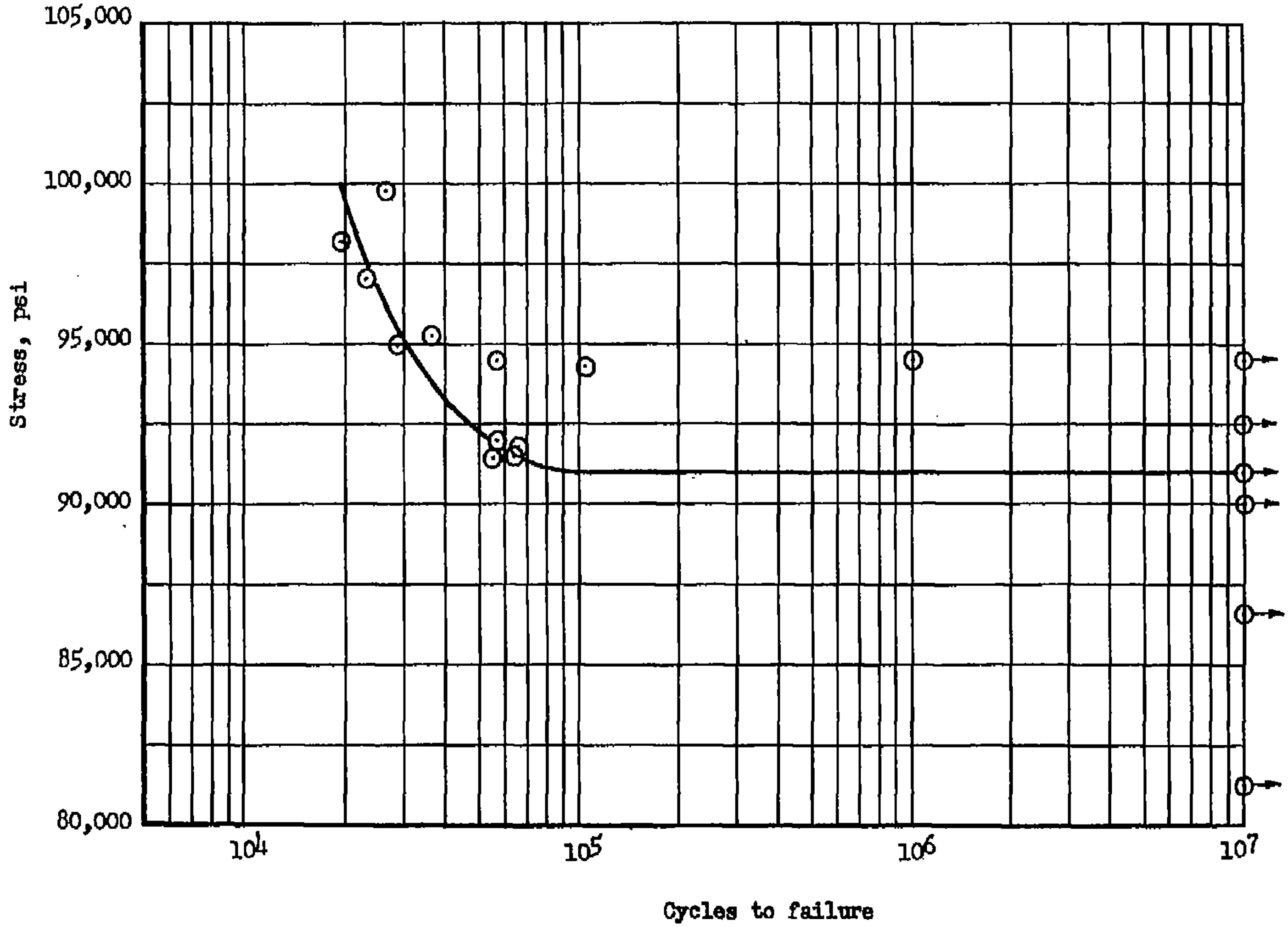
(f) At 1,000° F.

Figure 5.- Concluded.



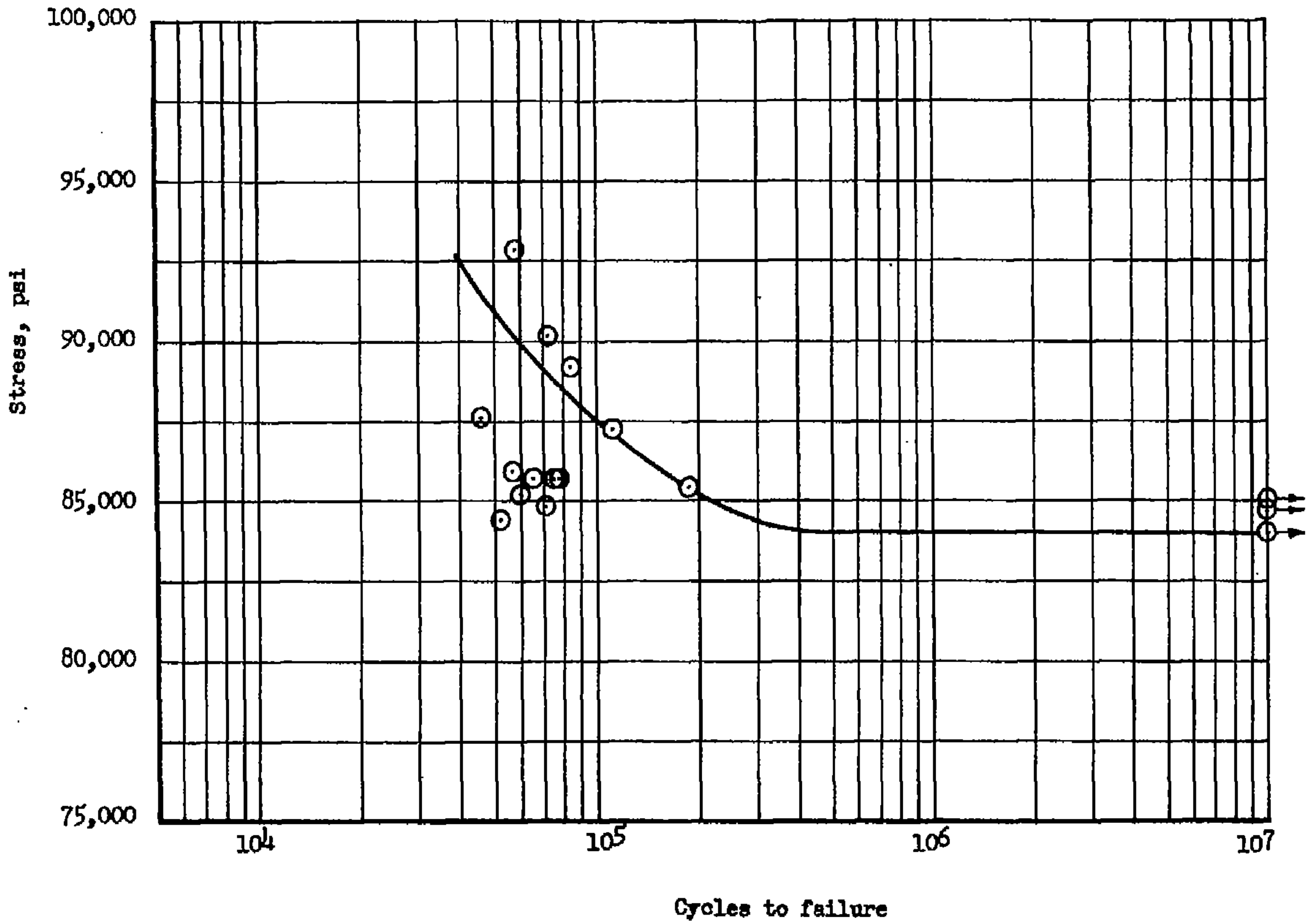
(b) 3Al-5Cr alloy.

Figure 6.- Variation of endurance strength with temperature.



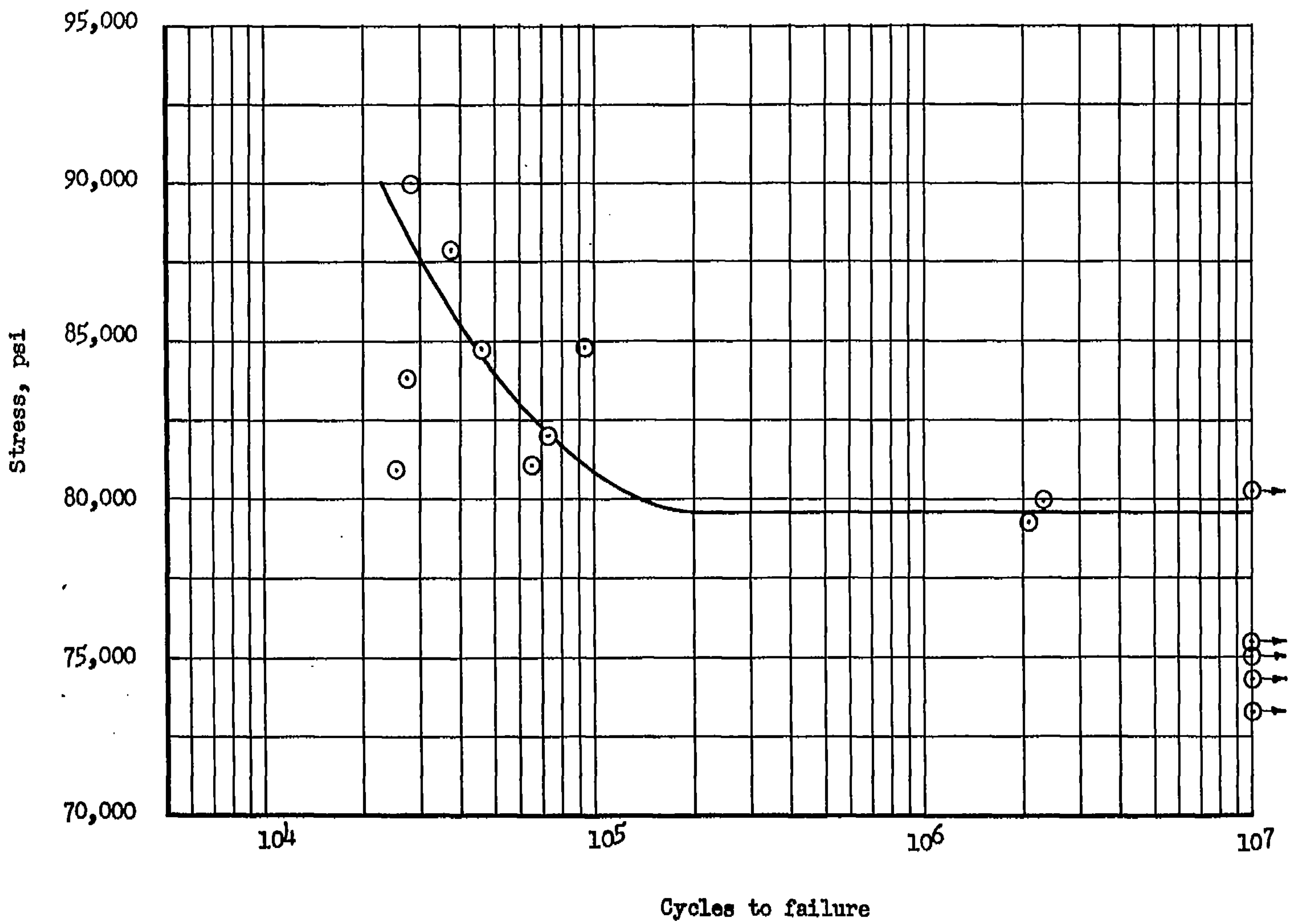
(a) At room temperature.

Figure 7.- Fatigue-test results for 3Al-5Cr titanium alloy.



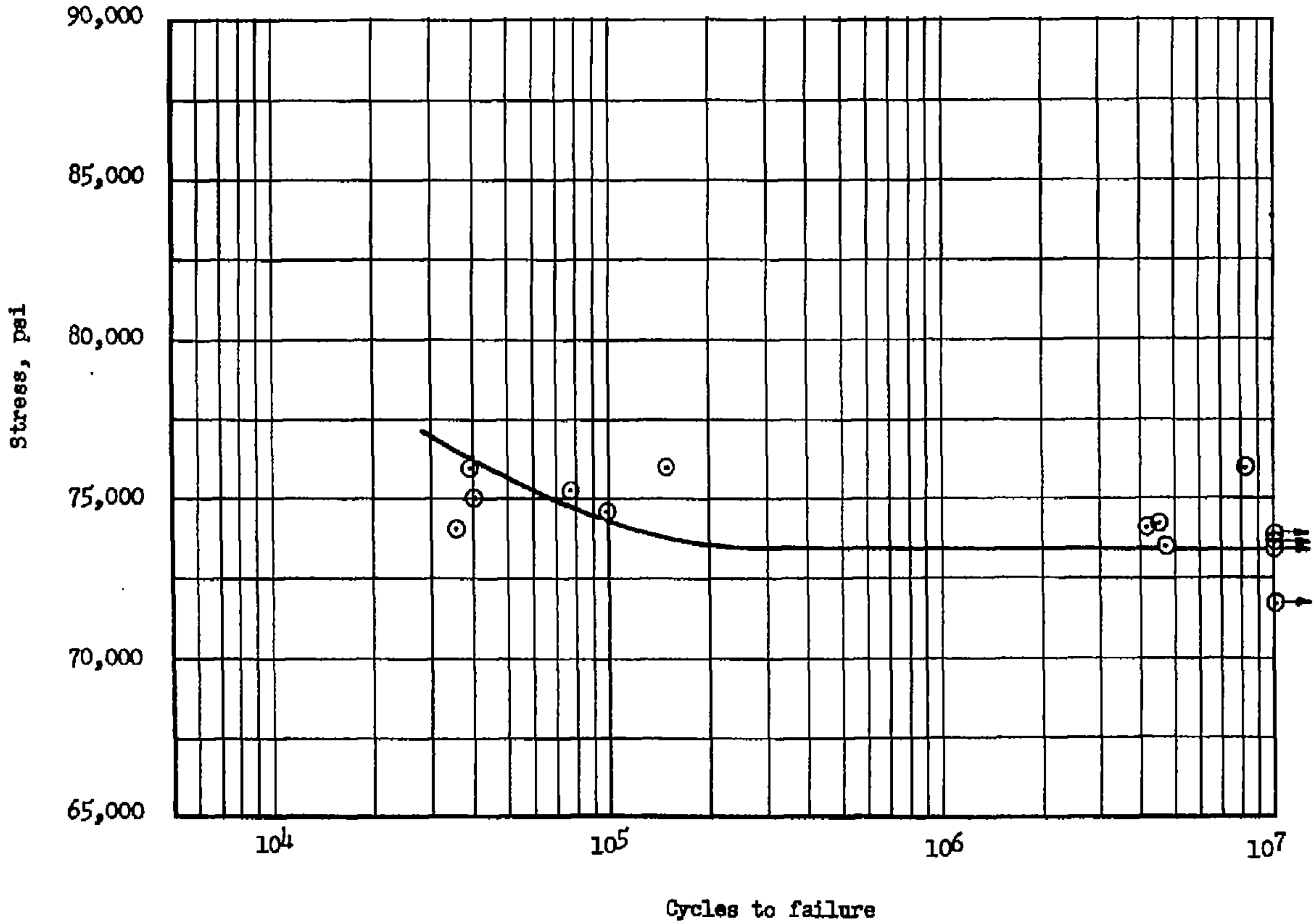
(b) At 200° F.

Figure 7.- Continued.



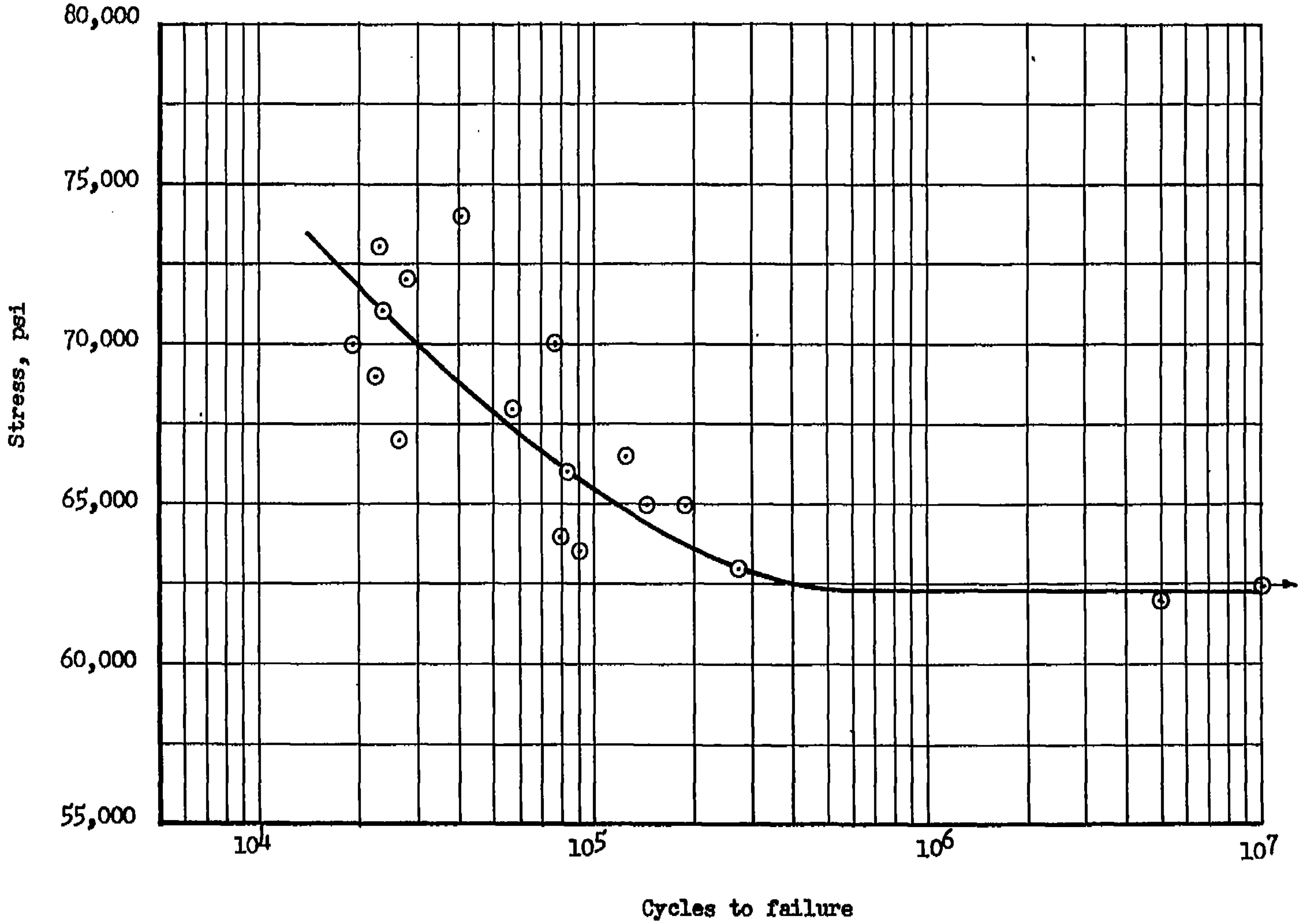
(c) At 400° F.

Figure 7.- Continued.



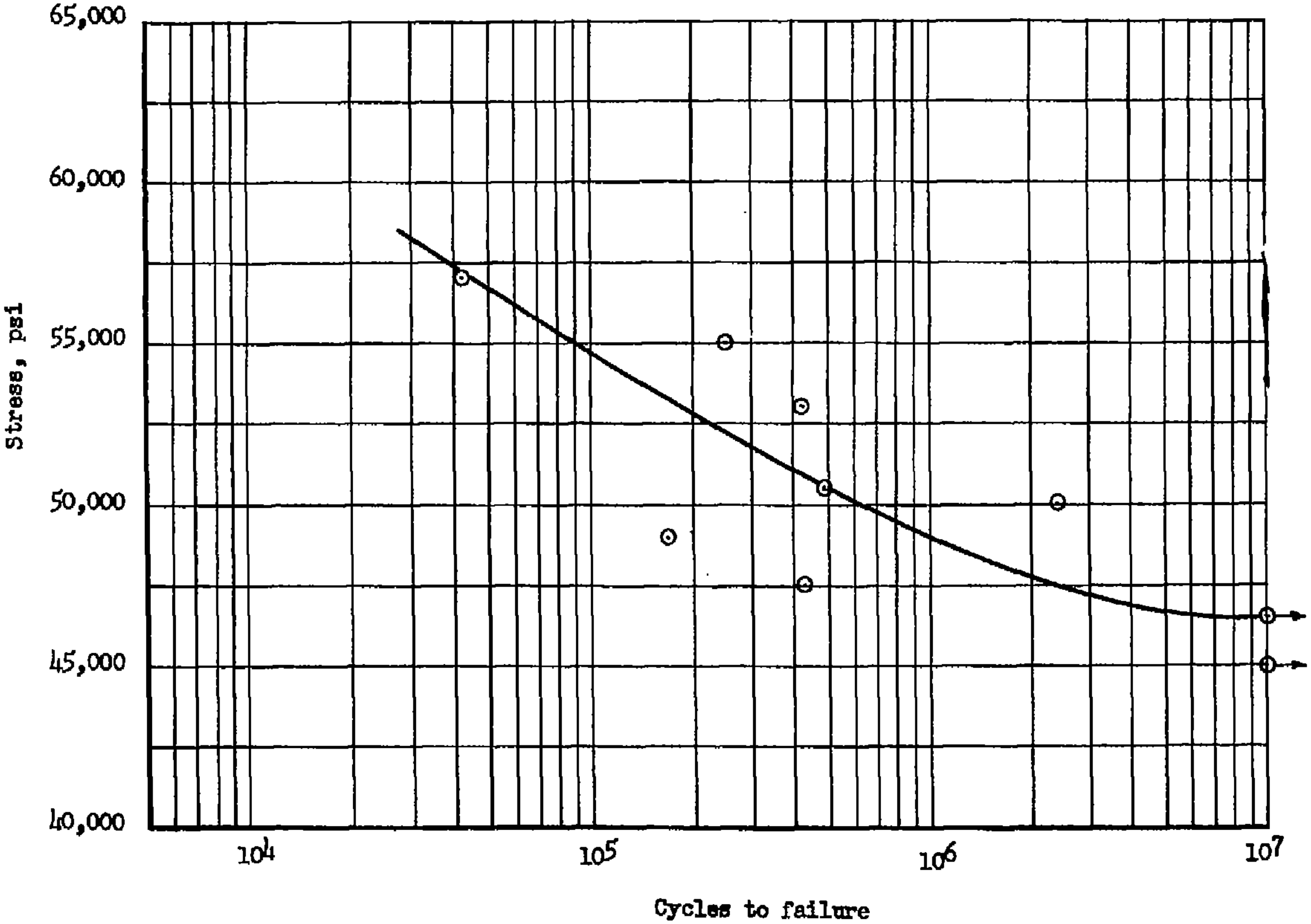
(d) At 600° F.

Figure 7.- Continued.



(e) At 800° F.

Figure 7.- Continued.



(f) At 1,000° F.

Figure 7.- Concluded.